

FCNC in SUSY models with non-universal A -terms

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Abstract. We study the inclusive branching ratio for $B \rightarrow X_s \gamma$ in a class of string-inspired SUSY models with non-universal soft-breaking A -terms. We show that $b \rightarrow s \gamma$ do not severely constrain the non-universality of these models and the parameter regions which are important for generating sizeable contribution to ε'/ε , of order 2×10^{-3} , are not excluded. We also show that the CP asymmetry of this decay is predicted to be much larger than the standard model prediction in a wide region of the parameter space. In particular, it can be of order 10–15% which can be accessible at B factories.

1. Introduction

The inclusive radiative decay $B \rightarrow X_s \gamma$ is known to provide a valuable constraint on any new physics beyond the standard model (SM). The most recent result reported by CLEO collaboration for the total (inclusive) B meson branching ratio $B \rightarrow X_s \gamma$ is [1]

$$\text{BR}(B \rightarrow X_s \gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4} \quad (1)$$

where the first error is statistical, the second systematic, and the third one accounts for model dependence. From this result the following bounds (each of them at 95% C.L.) are obtained

$$2.0 \times 10^{-4} < \text{BR}(B \rightarrow X_s \gamma) < 4.5 \times 10^{-4}. \quad (2)$$

In addition the ALEPH collaboration at LEP reported a compatible measurement of the corresponding branching ratio for b hadrons at the Z resonance [2].

It is well known that these experimental limits on $b \rightarrow s \gamma$ cause a dramatic reduction of the allowed parameter space in case of universal soft terms [3, 4]. However, it has been emphasized recently that the non-degenerate A -terms can generate the experimentally observed CP violation ε and ε'/ε even with a vanishing δ_{CKM} [5–8], i.e., fully supersymmetric CP violation in the kaon system is possible in a class of models with non-universal A -terms. So one may worry if these constraints would be even more severe in the case of the non-degenerate A -terms. The non-universal A -terms could enhance the gluino contribution to $b \rightarrow s \gamma$ decay which is usually very small in the universal case, being proportional to the mass insertions $(\delta_{LR}^d)_{23}$. It could also give large contributions to the chargino amplitude through the $(\delta_{LR}^u)_{23}$. Therefore a careful

analysis of the $b \rightarrow s\gamma$ predictions, including the full SUSY contributions, is necessary in this scenario.

In most of analysis universal or degenerate A -terms have been assumed, i.e., $(A_{U,D,L})_{ij} = A$ or $(A_{U,D,L})_{ij} = A_{U,D,L}$. This is certainly a nice simplifying assumption, but it removes some interesting degrees of freedom. For example, every A -term would, in general have an independent CP phase, and in principle we would have $27(= 3 \times 3 \times 3)$ independent CP phases. However, in the universal assumption only one independent CP phase is allowed. The situation drastically changes if we are to allow for non-degenerate A terms with different and independent CP phases. For example, the off-diagonal element of the squark (mass)² matrix, say $(M_Q^2)_{12}$, includes the term proportional to $(A_U)_{1i}(A_U^\dagger)_{i2}$. However, in the universal or the degenerate case this term is always real. Furthermore, these off-diagonal elements play an important role in ε and ε'/ε [6–8].

The major bulk of this talk will be devoted to the discussion of the $b \rightarrow s\gamma$ constraints for the SUSY models with non-universal A -terms studied in Refs. [6–8] following the work down in Ref. [9]. We will also mention to the effect of the flavour-dependent phases of the A -terms on the CP asymmetry in the inclusive $B \rightarrow X_s\gamma$ decay [10].

2. String inspired models with non-degenerate A -terms

In this work we consider the class of string inspired model which has been recently studied in Refs. [6–8]. In this class of models, the trilinear A -terms of the soft SUSY breaking are non-universal. It was shown that this non-universality among the A -terms plays an important role on CP violating processes. In particular, it has been shown that non-degenerate A -parameters can generate the experimentally observed CP violation ε and ε'/ε even with a vanishing δ_{CKM} .

Here we consider two models for non-degenerate A -terms. The first model (model A) is based on weakly coupled heterotic strings, where the dilaton and the moduli fields contribute to SUSY breaking [11]. The second model (model B) is based on type I string theory where the gauge group $SU(3) \times U(1)_Y$ is originated from the 9 brane and the gauge group $SU(2)$ is originated from one of the 5 branes [12].

2.1. Model A

We start with the weakly coupled string-inspired supergravity theory. In this class of models, it is assumed that the superpotential of the dilaton (S) and moduli (T) fields is generated by some non-perturbative mechanism and the F -terms of S and T contribute to the SUSY breaking. Then one can parametrize the F -terms as [11]

$$F^S = \sqrt{3}m_{3/2}(S + S^*) \sin \theta, \quad F^T = m_{3/2}(T + T^*) \cos \theta. \quad (3)$$

Here $m_{3/2}$ is the gravitino mass, n_i is the modular weight and $\tan \theta$ corresponds to the ratio between the F -terms of S and T . In this framework, the soft scalar masses m_i and

the gaugino masses M_a are given by [11]

$$m_i^2 = m_{3/2}^2(1 + n_i \cos^2 \theta), \quad (4)$$

$$M_a = \sqrt{3}m_{3/2} \sin \theta. \quad (5)$$

The $A^{u,d}$ -terms are written as

$$(A^{u,d})_{ij} = -\sqrt{3}m_{3/2} \sin \theta - m_{3/2} \cos \theta (3 + n_i + n_j + n_{H_{u,d}}), \quad (6)$$

where $n_{i,j,k}$ are the modular weights of the fields that are coupled by this A -term. If we assign $n_i = -1$ for the third family and $n_i = -2$ for the first and second families (we also assume that $n_{H_1} = -1$ and $n_{H_2} = -2$) we find the following texture for the A -parameter matrix at the string scale

$$A^{u,d} = \begin{pmatrix} x_{u,d} & x_{u,d} & y_{u,d} \\ x_{u,d} & x_{u,d} & y_{u,d} \\ y_{u,d} & y_{u,d} & z_{u,d} \end{pmatrix}, \quad (7)$$

where

$$x_u = m_{3/2}(-\sqrt{3} \sin \theta + 3 \cos \theta), \quad (8)$$

$$x_d = y_u = m_{3/2}(-\sqrt{3} \sin \theta + 2 \cos \theta), \quad (9)$$

$$y_d = z_u = m_{3/2}(-\sqrt{3} \sin \theta + \cos \theta), \quad (10)$$

$$z_d = -\sqrt{3}m_{3/2} \sin \theta. \quad (11)$$

The non-universality of this model is parameterized by the angle θ and the value $\theta = \pi/2$ corresponds to the universal limit for the soft terms. In order to avoid negative mass squared in the scalar masses we restrict ourselves to the case with $\cos^2 \theta < 1/2$. Such restriction on θ makes the non-universality in the whole soft SUSY breaking terms very limited. However, as shown in [6, 7], this small range of variation for the non-universality is enough to generate sizeable SUSY CP violations in K system.

2.2. Model B

This model is based on type I string theory and like model A, it is a good candidate for generating sizeable SUSY CP violations. In type I string theory, non-universality in the scalar masses, A -terms and gaugino masses can be naturally obtained [12]. Type I models contain either 9 branes and three types of $5_i (i = 1, 2, 3)$ branes or 7_i branes and 3 branes. From the phenomenological point of view there is no difference between these two scenarios. Here we consider the same model used in Ref. [8], where the gauge group $SU(3)_C \times U(1)_Y$ is associated with 9 brane while $SU(2)_L$ is associated with 5_1 brane.

If SUSY breaking is analysed, as in model A, in terms of the vevs of the dilaton and moduli fields [12]

$$F^S = \sqrt{3}m_{3/2}(S + S^*) \sin \theta, \quad F^{T_i} = m_{3/2}(T_i + T_i^*)\Theta_i \cos \theta, \quad (12)$$

where the angle θ and the parameter Θ_i with $\sum_i |\Theta_i|^2 = 1$, just parametrize the direction of the goldstino in the S and T_i fields space. Within this framework, the gaugino masses

are [12]

$$M_1 = M_3 = \sqrt{3}m_{3/2} \sin \theta, \quad (13)$$

$$M_2 = \sqrt{3}m_{3/2}\Theta_1 \cos \theta. \quad (14)$$

In this case the quark doublets and the Higgs fields are assigned to the open string which spans between the 5₁ and 9 branes. While the quark singlets correspond to the open string which starts and ends on the 9 brane, such open string includes three sectors which correspond to the three complex compact dimensions. If we assign the quark singlets to different sectors we obtain non-universal A -terms. It turns out that in this model the trilinear couplings A^u and A^d are given by [8, 12]

$$A^u = A^d = \begin{pmatrix} x & y & z \\ x & y & z \\ x & y & z \end{pmatrix}, \quad (15)$$

where

$$x = -\sqrt{3}m_{3/2}(\sin \theta + (\Theta_1 - \Theta_3) \cos \theta), \quad (16)$$

$$y = -\sqrt{3}m_{3/2}(\sin \theta + (\Theta_1 - \Theta_2) \cos \theta), \quad (17)$$

$$z = -\sqrt{3}m_{3/2} \sin \theta. \quad (18)$$

The soft scalar masses for quark-doublets and Higgs fields (m_L^2), and the quark-singlets ($m_{R_i}^2$) are given by

$$m_L^2 = m_{3/2}^2 \left(1 - \frac{3}{2}(1 - \Theta_1^2) \cos^2 \theta \right), \quad (19)$$

$$m_{R_i}^2 = m_{3/2}^2 \left(1 - 3\Theta_i^2 \cos^2 \theta \right), \quad (20)$$

where i refers to the three families. For $\Theta_i = 1/\sqrt{3}$ the A -terms and the scalar masses are universal while the gaugino masses could be non-universal. The universal gaugino masses are obtained at $\theta = \pi/6$.

In models with non-degenerate A -terms we have to fix the Yukawa matrices to completely specify the model. Here we assume that the Yukawa texture has the following form

$$Y^u = \frac{1}{v \cos \beta} \text{diag}(m_u, m_c, m_t), \quad Y^d = \frac{1}{v \sin \beta} V^\dagger \cdot \text{diag}(m_d, m_s, m_b) \cdot V \quad (21)$$

3. $b \rightarrow s\gamma$ constraints vs. non-universality

Theoretical study of $b \rightarrow s\gamma$ decay is given by the effective Hamiltonian

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{32}^* V_{33} \sum_{i=1}^8 C_i(\mu_b) Q_i(\mu_b) \quad (22)$$

where the complete basis of operators in the SM can be found in Ref. [13]. Recently the main theoretical uncertainties present in the previous leading order (LO) SM calculations have been reduced by including the NLO corrections to the $b \rightarrow s\gamma$ decay, through the calculation of the three-loop anomalous dimension matrix of the effective theory [13].

The relevant SUSY contributions to the effective Hamiltonian in Eq.(22) affect only the Q_7 and Q_8 operators, the expression for these operators are given (in the usual notation) by

$$\begin{aligned} Q_7 &= \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} , \\ Q_8 &= \frac{g_s}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G_{\mu\nu}^a . \end{aligned} \quad (23)$$

The Wilson coefficients $C_i(\mu)$ are evaluated at the renormalization scale $\mu_b \simeq O(m_b)$ by including the NLO corrections [13]. They can be formally decomposed as follows

$$C_i(\mu) = C_i^{(0)}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)}(\mu) + \mathcal{O}(\alpha_s^2). \quad (24)$$

where $C_i^{(0)}$ and $C_i^{(1)}$ stand for the LO and NLO order respectively. The SUSY contributions to the Wilson coefficients $C_{7,8}^{(0,1)}$ are obtained by calculating the $b \rightarrow s\gamma$ and $b \rightarrow sg$ amplitudes at EW scale respectively. The LO contributions to these amplitudes are given by the 1-loop magnetic-dipole and chromomagnetic dipole penguin diagrams respectively, mediated by charged Higgs boson, chargino, gluino, and neutralino exchanges. The corresponding results for these amplitudes can be found in Ref.[4]. We point out that the SUSY models with non-universal A -terms may induce non-negligible contributions to the dipole operators $\tilde{Q}_{7,8}$ which have opposite chirality with respect to $Q_{7,8}$. It is worth mentioning that these operators are also induced in the SM and in the MSSM with supergravity scenario, but their contributions are negligible being suppressed by terms of order $\mathcal{O}(m_s/m_b)$. In particular in MSSM, due to the universality of the A -terms, the gluino and chargino contributions to $\tilde{Q}_{7,8}$ turn out to be of order $\mathcal{O}(m_s/m_b)$. This argument does not hold in the models with non-universal A -terms and in particular in our case. It can be simply understood by using the mass insertion method [14]. For instance, the gluino contributions to Q_7 and \tilde{Q}_7 operators are proportional to $(\delta_{LR}^d)_{23} \simeq (S_{DL} Y_d^{A*} S_{DR}^\dagger)_{23}/m_{\tilde{q}}^2$ and $(\delta_{RL}^d)_{23} \simeq (S_{DR} Y_d^A S_{DL}^\dagger)_{23}/m_{\tilde{q}}^2$ respectively. Since the A^D matrix is symmetric in model A and $A_{ij}^D \simeq A_{ji}^D$ in model B, then $(\delta_{LR}^d)_{23} \simeq (\delta_{RL}^d)_{23}$. Then in our case we should consistently take into account the SUSY contributions to \tilde{Q}_7 in $b \rightarrow s\gamma$. Analogous considerations hold for the operator \tilde{Q}_8 .

By taking into account the above considerations regarding the operators $\tilde{Q}_{7,8}$, the new physics effects in $b \rightarrow s\gamma$ can be parametrized in a model independent way by introducing the so called $R_{7,8}$ and $\tilde{R}_{7,8}$ parameters defined at EW scale as

$$R_{7,8} = \frac{(C_{7,8}^{(0)} - C_{7,8}^{(0)SM})}{C_{7,8}^{(0)SM}}, \quad \tilde{R}_{7,8} = \frac{\tilde{C}_{7,8}^{(0)}}{C_{7,8}^{(0)SM}}, \quad (25)$$

where $C_{7,8}$ include the total contribution while $C_{7,8}^{SM}$ contains only the SM ones. Note that in $\tilde{C}_{7,8}$, which are the corresponding Wilson coefficients for $\tilde{Q}_{7,8}$ respectively, we have set to zero the SM contribution. In Ref. [4] only the expressions for the $R_{7,8}$ are given, the corresponding expressions for $\tilde{R}_{7,8}$ are given in Ref. [9]. The general parametrization of the branching ratio in terms of the new physics contributions is

given by [15].

$$BR(B \rightarrow X_s \gamma) = (3.29 \pm 0.33) \times 10^{-4} \left(1 + 0.622 Re[R_7] + 0.090(|R_7|^2 + |\tilde{R}_7|^2) + 0.066 Re[R_8] + 0.019(Re[R_7 R_8^*] + Re[\tilde{R}_7 \tilde{R}_8^*]) + 0.002(|R_8|^2 + |\tilde{R}_8|^2) \right), \quad (26)$$

where the overall SM uncertainty has been factorized outside. We have checked explicitly that the result in Eq.(26) is in agreement with the corresponding one used in Ref. [16].

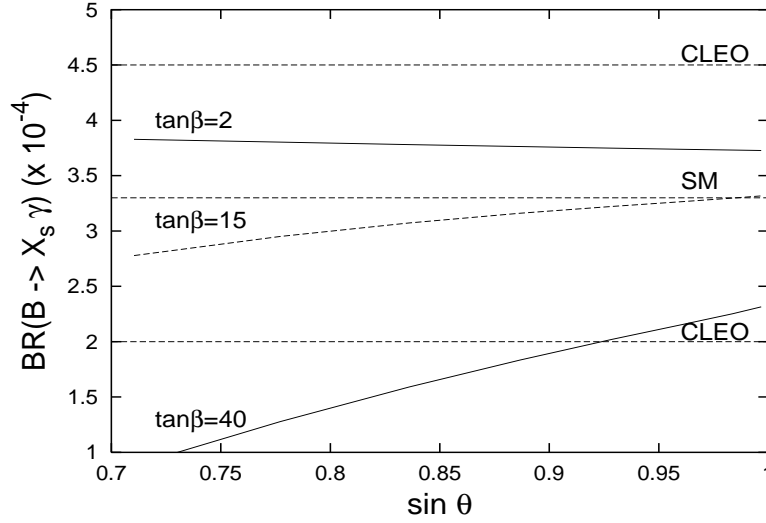


Figure 1. The $BR(B \rightarrow X_s \gamma)$ versus $\sin \theta$ in model A, for $\mu > 0$, $m_{3/2} = 150$ GeV and $\tan \beta = 2, 15, 40$.

In Figs. [1] we plot the results for the branching ratio $BR(B \rightarrow X_s \gamma)$, in model A, versus $\sin \theta$ for different values of $\tan \beta$, $m_{3/2} = 150$ and $\mu > 0$ (for $\mu < 0$, as in MSSM, almost the whole range of the parameter space is excluded). The main message arising from these results is that the sensitivity of $BR(B \rightarrow X_s \gamma)$ respect to $\sin \theta$ increases with $\tan \beta$. In particular for the low $\tan \beta$ region the $b \rightarrow s \gamma$ result does not differ significantly from the universal case. In the large $\tan \beta$ region, $\tan \beta = 15 - 40$, the CLEO measurement of $b \rightarrow s \gamma$ set severe constraints on the angle θ for low gravitino masses.

In Fig.[2] we plot the branching ratio $BR(B \rightarrow X_s \gamma)$, in model B, versus $\tan \beta$ for three different values of Θ_1, Θ_2 (see the figure caption) which are representative examples for universal and highly non-universal cases. From these figures it is clear that $BR(B \rightarrow X_s \gamma)$ is not very sensitive to the values of Θ_i 's parameters, even at very large $\tan \beta$, unlike model A. The constraints from CLEO measurement are almost the same in the universal and non-universal cases. For $\mu > 0$ the branching ratio is constrained from the lower bound of CLEO only at very large $\tan \beta$, while for $\mu < 0$ the branching ratio is almost excluded except at low $\tan \beta$.

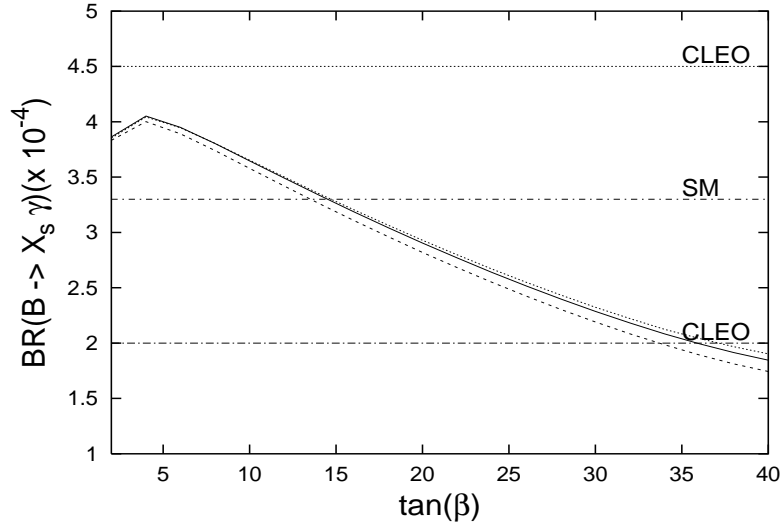


Figure 2. The branching ratio $\text{BR}(B \rightarrow X_s \gamma)$ versus $\tan \beta$ in model B, for $\mu > 0$, $m_{3/2} = 150$ GeV, and for some values of $(\Theta_1, \Theta_2) = (1/\sqrt{3}, 1/\sqrt{3})$, $(0.9, 0.2)$, $(0.6, 0.2)$, corresponding to the continuous, dashed, and dot-dashed lines respectively.

4. SUSY phases and CP asymmetry in $B \rightarrow X_s \gamma$ decays

Direct CP asymmetry in the inclusive radiative decay $B \rightarrow X_s \gamma$ is measured by the quantity

$$A_{CP}^{b \rightarrow s \gamma} = \frac{\Gamma(\bar{B} \rightarrow X_s \gamma) - \Gamma(B \rightarrow X_{\bar{s}} \gamma)}{\Gamma(\bar{B} \rightarrow X_s \gamma) + \Gamma(B \rightarrow X_{\bar{s}} \gamma)}. \quad (27)$$

The Standard Model (SM) prediction for this asymmetry is very small, less than 1%. Thus, the observation of sizeable asymmetry in the decay $B \rightarrow X_s \gamma$ would be a clean signal of new physics.

The most recent result reported by CLEO collaboration for the CP asymmetry in these decays is [17]

$$-9\% < A_{CP}^{b \rightarrow s \gamma} < 42\% , \quad (28)$$

and it is expected that the measurements of $A_{CP}^{b \rightarrow s \gamma}$ will be improved in the next few years at the B -factories.

Supersymmetric predictions for $A_{CP}^{b \rightarrow s \gamma}$ are strongly dependent on the flavour structure of the soft breaking terms. It was shown that in the universal case, as in the minimal supergravity models, the prediction of the asymmetry is less than 2%, since in this case the electric dipole moments (EDM) of the electron and neutron constrain the SUSY CP-violating phases to be very small [18, 19]. we explore the effect of these large flavour-dependent phases on inducing a direct CP violation in $B \rightarrow X_s \gamma$ decay. We will show that the values of the asymmetry $A_{CP}^{b \rightarrow s \gamma}$ in this class of models are much larger than the SM prediction in a wide region of the parameter space allowed by experiments, namely the EDM experimental limits and the bounds on the branching ratio of $B \rightarrow X_s \gamma$. The enhancement of $A_{CP}^{b \rightarrow s \gamma}$ is due to the important contributions

from gluino-mediated diagrams, in this scenario, in addition to the usual chargino and charged Higgs contributions.

The expression for the asymmetry $A_{CP}^{b \rightarrow s \gamma}$, corrected to next-to-leading order is given by [20]

$$A_{CP}^{b \rightarrow s \gamma} = \frac{4\alpha_s(m_b)}{9|C_7|^2} \left\{ \left[\frac{10}{9} - 2z (v(z) + b(z, \delta)) \right] \text{Im}[C_2 C_7^*] \right. \\ \left. + \text{Im}[C_7 C_8^*] + \frac{2}{3} z b(z, \delta) \text{Im}[C_2 C_8^*] \right\}, \quad (29)$$

where $z = m_c^2/m_b^2$. The functions $v(z)$ and $b(z, \delta)$ can be found in Ref.[20]. The parameter δ is related to the experimental cut on the photon energy, $E_\gamma > (1 - \delta)m_b/2$, which is assumed to be 0.9. We neglect the very small effect of the CP-violating phase in the CKM matrix. As mentioned above, SUSY models with non-universal A -terms may induce non-negligible contributions to the dipole operators $\tilde{Q}_{7,8}$ which have opposite chirality to $Q_{7,8}$. In the MSSM these contributions are suppressed by terms of order $\mathcal{O}(m_s/m_b)$ due to the universality of the A -terms. However, in our case we should take them into account. Denoting by $\tilde{C}_{7,8}$ the Wilson coefficients multiplying the new operators $\tilde{Q}_{7,8}$ the expression for the asymmetry in Eq.(29) will be modified by making the replacement

$$C_i C_j^* \rightarrow C_i C_j^* + \tilde{C}_i \tilde{C}_j^*. \quad (30)$$

The expressions for $\tilde{C}_{7,8}$ are given in Ref.[9] and $\tilde{C}_2 = 0$ (there is no operator similar to Q_2 containing right-handed quark fields).

Note that including these modifications (30) may enhance the branching ratio of $B \rightarrow X_s \gamma$ and reduce the CP asymmetry, since $|C_7|^2$ is replaced by $|C_7|^2 + |\tilde{C}_7|^2$ in the denominator of Eq.(29). If so, neglecting this contribution could lead to an incorrect conclusion.

In this class of models we consider here, the relevant and important phase for the CP asymmetry is the phase of the off-diagonal element A_{23} (ϕ_b). In Fig.1 we show the dependence of $A_{CP}^{b \rightarrow s \gamma}$ on ϕ_b for $m_{3/2} = 150$ GeV and $\tan \beta = 3$ and 10.

We see from Fig.[3] that the CP asymmetry $A_{CP}^{b \rightarrow s \gamma}$ can be as large as $\pm 15\%$, which can be accessible at the B-factories. Also this result does not require a light chargino as in the case considered in Ref. [21].

It is important to emphasize that the gluino contribution in this model gives the dominant contribution to the CP asymmetry $A_{CP}^{b \rightarrow s \gamma}$. We found that although the real parts of the gluino contributions to both of $C_{7,8}$ and $\tilde{C}_{7,8}$ are smaller than the real parts of the other contributions (but not negligible as in the case of universal A -terms), their imaginary parts are dominant and give with the imaginary parts of the chargino contribution the main contributions to $A_{CP}^{b \rightarrow s \gamma}$. It is clear that these contributions vanish for ϕ_b equal to a multiple of π and $A_{CP}^{b \rightarrow s \gamma}$ in this case is identically zero as Fig.1 shows. We also noted [10] that large values of CP asymmetry $A_{CP}^{b \rightarrow s \gamma}$ prefer small values for the branching ratio $BR(B \rightarrow X_s \gamma)$. This correlation is also found in Ref. [19].

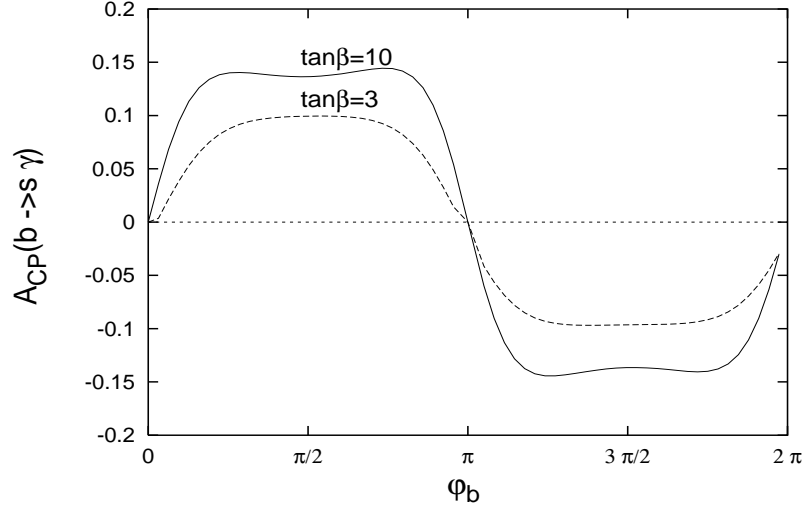


Figure 3. CP asymmetry $A_{CP}^{b \rightarrow s\gamma}$ as a function of the flavour-dependent phase ϕ_b , for $m_{3/2} \simeq 150$ GeV and $\tan\beta = 3$ and 10.

5. Conclusions

We analysed the constraints set by the $b \rightarrow s\gamma$ decay on a class of string inspired SUSY models with non-universal soft breaking A -terms. We found that the recent CLEO measurements on the total inclusive B meson branching ratio $\text{BR}(B \rightarrow X_s \gamma)$ do not set severe constraints on the non-universality of these models. In this respect we have found that the parameter regions which are important for generating sizeable contributions to ε'/ε [6–8], in particular the low $\tan\beta$ regions, are not excluded by $b \rightarrow s\gamma$ decay.

we have also considered the possible supersymmetric contribution to CP asymmetry in the inclusive $B \rightarrow X_s \gamma$ decay in model with non-universal A -terms. Contrary to the universal scenario, we find that the CP asymmetry in this class of models is predicted to be large in sizeable regions of the parameter space allowed by the experimental bounds, and may be possibly to be detected at B factories. We have shown that the flavour-dependent phases are crucial for this enhancing with respecting the severe bounds on the electric dipole moment of the neutron and electron.

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